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Four-fermion decay of Higgs bosons

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ABSTRACT

We calculate four-fermion decays of a Higgs boson via WW and/or ZZ intermediate states for Higgs masses below m_W. We examine models with a doubly-charged Higgs boson H^{++} and show that the four-fermion decay is the dominant mode for a wide range of parameter space. Existing searches for H^{++} in Z decays have not looked for this mode. We also derive four-fermion decay rate for a neutral Higgs boson.

1. Introduction

Although the standard model has been very successful in describing the interaction of elementary particles, all available tests are sensitive to its gauge part only. The Higgs sector of the theory remains totally untested. In the minimal standard model, the Higgs sector consists of a single doublet of Higgs fields, while two doublets exist in the minimal supersymmetric standard model. Although the doublet is the simplest possibility and is necessary to generate quark and lepton masses, there is no *a priori* reason that only Higgs doublets exist. In many extensions of the standard model, larger Higgs representations appear [1]. A characteristic particle common to these extensions is a doubly charged Higgs boson, which is not contained in models with doublets.

The smallest Higgs representation[‡1] containing a doubly charged Higgs is the triplet representation of SU(2) with hypercharge $Y = 1$. Such a triplet can generate a Majorana mass for neutrinos by a Yukawa coupling. The doubly charged Higgs boson H^{++} can decay to a same-sign charged lepton pair by this Yukawa coupling.

An important constraint on an extended Higgs sector comes from the so-called rho parameter [2] defined by

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} , \tag{1.1}$$

which is experimentally equal to one in a percent level. Models with only doublets satisfy $\rho = 1$ at the tree level, but those with an extended Higgs sector gives $\rho \neq 1$ in general. The $Y = 1$ triplet alone gives $\rho = 1/2$. The vacuum expectation value (vev) of the triplet has thus to be much smaller than the vev of the doublet.

‡1 We define Higgs field as a scalar field with nonzero vacuum expectation value. Our normalization of the weak hypercharge is $Q = I_3 + Y$.

A different possibility to give $\rho = 1$ has been proposed by Georgi *et al.* [3] and Chanowitz and Golden [4]. They introduced another triplet with $Y = 0$ and showed that $\rho = 1$ results if the two triplets have equal vev. Chanowitz and Golden wrote down a Higgs potential with a tree-level $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ symmetry to ensure $\rho = 1$. In this model, which we will call the tri-triplet model, the vev of the triplet can be as large as the vev of the doublet.

Search for H^{++} in Z decay has been performed by Mark II Collaboration at SLC [5] and OPAL Collaboration at LEP [6]. The H^{++} can be pair produced in Z decay with a sizable branching ratio if energetically allowed. They looked for same-sign lepton pairs coming from H^{++} decay. If the Yukawa coupling is very small, the lifetime of H^{++} becomes long enough that the particle does not decay in the detector. The OPAL Collaboration searched for doubly charged heavy particle tracks to cover this case. These searches have excluded a doubly charged Higgs almost up to the kinematical limit ($m_Z/2$) for most values of the Yukawa coupling.

In these searches, it is assumed that the same-sign lepton pair is the sole decay mode of H^{++}. However, it is possible that H^{++} decays to four fermions via a pair of virtual W^+. In this paper, we show that this decay mode can be the dominant mode of H^{++}, especially when the triplet vev is not small. The existing searches are thus not complete.

We also calculate the four-fermion decay rate of a neutral Higgs boson via WW and ZZ intermediate states.

2. $H^{++} \to f_1 \bar{f}_2 f_3 \bar{f}_4$

The interaction Lagrangian of H^{++} with two W's is derived from the Higgs kinetic term with covariant derivative, after replacing the neutral Higgs field by its vev. It can be written as

$$\mathcal{L} = \tfrac{1}{2} g m_W x \, H^{++} W_\mu W^\mu \, , \qquad (2.1)$$

where g is the SU(2) gauge coupling, m_W is the W mass, and x is a constant depending on the representation and vev of the Higgs field in which H^{++} is contained.

For the $Y = 1$ triplet

$$\chi = \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \end{pmatrix} \tag{2.2}$$

one finds

$$x = \frac{2\sqrt{2}\, v_3}{v} \; , \tag{2.3}$$

with $\langle \chi^0 \rangle = v_3/\sqrt{2}$, and the normalization $v \simeq 246\,\mathrm{GeV}$ is defined by $m_W = \frac{1}{2} g v$. In models with a $Y = 1$ triplet and one or more doublets, we have $v^2 = v_2^2 + 2v_3^2$, where v_2 is the vev of the standard Higgs doublet or the sum of vev squared for the doublets. As discussed earlier, v_3 is subject to a constraint from ρ. A recent analysis [7] gives $v_3 < 25\,\mathrm{GeV}$, which is translated to $x < 0.29$.

The tri-triplet model contains an additional $Y = 0$ triplet. Though the coupling is the same, v^2 is now given by $v^2 = v_2^2 + 4v_3^2$. The coupling is maximal when the triplet vev is dominant, in which case $x = \sqrt{2}$. Although the doublet vev cannot be too small (otherwise the top Yukawa coupling becomes strong), $x \sim 1$ is still allowed.[‡2] The HWW coupling can thus be quite sizable in both models.

Let us consider the process

$$H^{++}(q) \to f_1(p_1) + \bar{f}_2(p_2) + f_3(p_3) + \bar{f}_4(p_4) \tag{2.4}$$

via this coupling (the particle momenta are in the parenthesis). We are interested in the mass range $m_H < m_W$, in which decays to an on-shell W, $H^{++} \to W^+ W^+$

‡2 The rare decay $b \to s\gamma$ constrains the Yukawa coupling as a function of H^+ mass. Since cancellation occurs in the tri-triplet model, v_2 as small as $100\,\mathrm{GeV}$ is consistent with the data even for a H^+ mass around $50\,\mathrm{GeV}$ [8].

or $H^{++} \to W^+ f \bar{f}'$ are kinematically forbidden. We assume $f_1 \neq f_3$, $\bar{f}_2 \neq \bar{f}_4$ for a while and neglect the Kobayashi-Maskawa mixing. The Feynman graph for this process is shown in Fig. 1. The amplitude is

$$\begin{aligned}\mathcal{M} = -\frac{1}{8}\, x g^3 m_W \, & \frac{1}{\left[m_W^2 - (p_1+p_2)^2\right]\left[m_W^2 - (p_3+p_4)^2\right]} \\ & \times \bar{u}(p_1)\gamma_\mu(1-\gamma_5)v(p_2)\ \bar{u}(p_3)\gamma^\mu(1-\gamma_5)v(p_4)\ .\end{aligned} \tag{2.5}$$

The decay rate for massless fermions is calculated to be

$$\Gamma(H^{++} \to f_1\bar{f}_2 f_3 \bar{f}_4) = \frac{x^2 G_F^3 m_H^7}{576\sqrt{2}\,\pi^5}\, I\Big(\frac{m_H^2}{m_W^2}\Big)\ , \tag{2.6}$$

with the function $I(r)$ defined as

$$I(r) = \iint dx\, dy\, \frac{\bar{\beta}(x,y)\left[(1-x-y)^2 + 8xy\right]}{(1-rx)^2(1-ry)^2}\ , \tag{2.7}$$

where the integration is over the region x, $y > 0$, $\sqrt{x} + \sqrt{y} < 1$, and

$$\bar{\beta}(x,y) = \left[1 - 2(x+y) + (x-y)^2\right]^{1/2}\ . \tag{2.8}$$

In the light Higgs limit $r \to 0$, the integral may be done analytically:

$$I(0) = \frac{1}{20}\ . \tag{2.9}$$

We now turn to the case in which the two virtual W's decay to the same fermion pair, $f_1 = f_3$, $\bar{f}_2 = \bar{f}_4$. There are two Feynman graphs for this process as shown in Fig. 2. The amplitude after Fierz rearrangement is

$$\begin{aligned}\mathcal{M} = -\frac{1}{8}\, x g^3 m_W & \left\{ \frac{1}{\left[m_W^2 - (p_1+p_2)^2\right]\left[m_W^2 - (p_3+p_4)^2\right]} \right. \\ & \qquad \left. + \frac{1}{\left[m_W^2 - (p_1+p_4)^2\right]\left[m_W^2 - (p_3+p_2)^2\right]} \right\} \\ & \times \bar{u}(p_1)\gamma_\mu(1-\gamma_5)v(p_2)\ \bar{u}(p_3)\gamma^\mu(1-\gamma_5)v(p_4)\ .\end{aligned} \tag{2.10}$$

In the light Higgs limit, we can easily see that the two contributions have perfectly constructive interference. The decay rate thus gains a factor of 4, but the total

rate has to be multiplied by 1/4 to account for the two identical particle pairs in the final state. The final result in this limit thus turns out to be the same[‡3] as Eq. (2.6).

As the Higgs mass increases, the interference of the two amplitudes becomes less complete. The two contributions becomes totally incoherent above the WW threshold, where the width for the identical fermions is relatively suppressed by a factor of 2. This can be easily understood because two channels exist for the different fermion final state ($W_1 \to f_1\bar{f}_2$, $W_2 \to f_3\bar{f}_4$ and $W_1 \to f_3\bar{f}_4$, $W_2 \to f_1\bar{f}_2$) whereas only one channel is possible for the identical final state ($W_1 \to f_1\bar{f}_2$, $W_2 \to f_1\bar{f}_2$).

Taking $e^+\nu_e$, $\mu^+\nu_\mu$, $\tau^+\nu_\tau$, $u\bar{d}$ and $c\bar{s}$ pairs as the final states (with due attention to the color factor), we find the total rate for $H^{++} \to f\bar{f}f\bar{f}$

$$\Gamma(H^{++} \to f\bar{f}f\bar{f}) = (36+9\zeta)\frac{x^2G_F^3m_H^7}{576\sqrt{2}\pi^5}\, I\Big(\frac{m_H^2}{m_W^2}\Big)\,, \tag{2.11}$$

where $1/2 \le \zeta \le 1$ and $\zeta \to 1$ at $m_H \to 0$. Since we are not concerned with an error of order 10%, we will use $\zeta = 1$ in the following analysis.

The decay width (2.11) for $x = 1$ is plotted in Fig. 3 as a function of the Higgs mass. The pointlike approximation using (2.9) works quite well for $m_H \lesssim 50$ GeV: The difference from the exact result is less than 20%.

‡3 The case $f_1 = f_3$ but $\bar{f}_2 \neq \bar{f}_4$ (e.g. $u\bar{d}u\bar{s}$ final state with identical colors) appears if the Kobayashi-Maskawa mixing is retained. The amplitude has two contributions with constructive interference, but the identical particle factor is only 1/2. The net result is a factor 2 increase compared to those discussed in the text.

3. H^{++} Lifetime and Branching Ratio

Another important decay of H^{++} is the same-sign dilepton mode,[‡4] which has been discussed in the literature [10]. Here we rederive the results to fix our notation.

The $Y = 1$ triplet can couple to a pair of left-handed leptons.[‡5] We write the Yukawa coupling as

$$\begin{aligned}\mathcal{L} &= -\tfrac{1}{2}\sum_{i,j} h_{ij}\bar{L}_i^c \tau^a \chi^a L_j + \text{h.c.} \\ &= -\frac{1}{\sqrt{2}}\sum_{i,j} h_{ij}\left(\bar{\ell}_i^c \ell_{jL}\,\chi^{++} + \sqrt{2}\,\bar{\nu}_i^c \ell_{jL}\,\chi^{+} + \bar{\nu}_i^c \nu_{jL}\,\chi^{0}\right) + \text{h.c.}\ ,\end{aligned} \tag{3.1}$$

where i, j are the generation indices, h_{ij} forms a symmetric Yukawa coupling matrix, and

$$L_i = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}_L , \qquad L_i^c = i\tau_2 C \bar{L}_i^T = \begin{pmatrix} \ell_i^c \\ -\nu_i^c \end{pmatrix} , \tag{3.2}$$

$$\tau^a \chi^a = \begin{pmatrix} \chi^+ & \sqrt{2}\chi^{++} \\ -\sqrt{2}\chi^0 & -\chi^+ \end{pmatrix} . \tag{3.3}$$

The neutrino mass matrix is given by $(m_\nu)_{ij} = h_{ij} v_3$. The dilepton decay rate is for an identical lepton pair

$$\Gamma(H^{++} \to \ell^+ \ell^+) = \frac{|h_{\ell\ell}|^2}{16\pi}\, m_H\ , \tag{3.4}$$

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‡4 We do not consider decay modes with a Higgs in the final state, e.g., $H^{++} \to H^+ f \bar{f}'$ and $H^{++} \to H^+ H^+$, because the LEP limit [9] $m(H^+) \gtrsim 42\,\text{GeV}$ makes these decays unlikely to be important.

‡5 Besides the $Y = 1$ triplet, $Y = 2$ singlet (which appear in left-right symmetric models) can couple to a (right-handed) charged lepton pair. These two exhausts possible Higgs representations which can decay to $\ell^+\ell^+$.

and for a different lepton pair $\ell \neq \ell'$

$$\Gamma(H^{++} \to \ell^+ \ell'^+) = \frac{|h_{\ell\ell'}|^2}{8\pi}\, m_H \ . \tag{3.5}$$

The total decay rate is given by the sum of Eq. (2.11) and these dilepton decay rates. For definiteness, we represent the dilepton decays by that with largest $h_{\ell\ell'}$, which we take to be $\tau\tau$. The lifetime is thus

$$\tau^{-1} = \Gamma(f\bar{f}f\bar{f}) + \Gamma(\tau\tau) \ . \tag{3.6}$$

The H^{++} can be pair produced in Z decay if kinematically allowed. The partial width is

$$\Gamma(Z \to H^{++}H^{--}) = \frac{G_F m_Z^3}{6\sqrt{2}\pi}\,(I_3 - 2\sin^2\theta_W)^2 \beta^3 \ , \tag{3.7}$$

where $I_3 = 2 - Y$, $\beta = (1 - 4m_H^2/m_Z^2)^{1/2}$.

The experimental signature of H^{++} production depends on the lifetime and dominant decay mode. There are three distinct regions depending on m_H, x, and $h_{\tau\tau}$, as is demonstrated in Fig. 4 for $m_H = 40\,\mathrm{GeV}$.

First, if the decay length $\ell = \gamma\beta c\tau$ is larger than the size of the charged track detector, an event looks like a pair of doubly charged stable particles. This happens in the lower left side of Fig. 4, in which lines corresponding to $\ell = 1\,\mathrm{m}$ and $\ell = 1\,\mathrm{cm}$ are shown.

If ℓ is sufficiently small that the decay products are visible in the detector, the signature depends on the dominant decay mode. We define the ratio

$$R = \frac{\Gamma(H^{++} \to f\bar{f}f\bar{f})}{\Gamma(H^{++} \to \tau^+\tau^+)} \tag{3.8}$$

which measures the relative importance of the two decay modes. Lines corresponding to $R = 0.1$, 1, and 10 are shown in Fig. 4. In the region both $R \ll 1$ and ℓ are small, an event contains four leptons. This is the case if the Yukawa coupling is rather large and the triplet vev is small.

Finally, if ℓ is small and $R \gg 1$, the four-fermion mode dominates and an event contains eight quarks/leptons in the final state. This can occur in the lower right part of the plot. This region grows rapidly for a larger Higgs mass because of the m_H^7 dependence of the width.

As mentioned earlier, the first two signatures have been sought for [5, 6], but the last possibility has hitherto overlooked. In this case, a mass limit for H^{++} can still be derived from the total Z width. Reference [6] gives a limit of 30.4 GeV (95%CL) for $Y = 1$. Direct search for the eight-fermion final states would improve the bound up to the kinematical limit of 45 GeV.

4. Four-fermion Decay of Neutral Higgs Boson

In general, a neutral Higgs boson H^0 couples with a W and Z pair:

$$\mathcal{L} = g m_W x_c W_\mu^\dagger W^\mu H^0 + \tfrac{1}{2} g_Z m_Z x_n Z_\mu Z^\mu H^0 \ , \tag{4.1}$$

where $g_Z = g/\cos\theta_W$. In the standard model, we have $x_c = x_n = 1$ for the neutral Higgs boson. These couplings induce the four-fermion decay mode $H^0 \to f_1 \bar{f}_2 f_3 \bar{f}_4$. The decay width can be obtained in a similar way as for H^{++}. There are two possible intermediate states $W^{+*}W^{-*}$ and Z^*Z^*. Some of the final states (e.g. $e^+e^-\nu_e\bar{\nu}_e$) receive interefering contribution from both intermediate states. Another set of final states like $e^+e^-e^+e^-$ have two diagrams with Z^*Z^* intermediate state. Taking these complications in account, we find the decay rate for $m_H \ll m_W$

$$\begin{aligned}\Gamma(H^0 \to f\bar{f}f\bar{f}) = {} & \frac{G_F^3 m_H^7}{11520\sqrt{2}\,\pi^5} \\ & \times \Big\{ 81 x_c^2 + \big[12(v_\nu{+}a_\nu)(v_e{+}a_e) + 24(v_u{+}a_u)(v_d{+}a_d)\big] x_c x_n \\ & \quad + \Big[12 \sum_f k_f \big(v_f^4{+}6v_f^2 a_f^2{+}a_f^4\big) + 72 \Big(\sum_f k_f \big(v_f^2{+}a_f^2\big)\Big)^2 \Big] x_n^2 \ \Big\} \ ,\end{aligned} \tag{4.2}$$

where the sum fur f runs over $f = \nu,\, e,\, u,\, d$,

$$k_f = \begin{cases} 1 & f = \nu,\, e, \\ 2 & f = u, \\ 3 & f = d, \end{cases} \tag{4.3}$$

and $v_f = \frac{1}{2} I_3(f_L) - Q_f \sin^2\theta_W$, $a_f = \frac{1}{2} I_3(f_L)$. The expression within $\{\}$ is equal to 103.8 for $\sin^2\theta_W = 0.23$, $x_c = x_n = 1$, most of which comes from the WW intermediate state. The decay rate is much smaller than that of $H^0 \to f\bar{f}$ via the Yukawa coupling. This result may, however, be relevant for a neutral Higgs in a nondoublet representation, which cannot couple to a fermion pair. Such a particle has been searched for by ALEPH Collaboration at LEP [13]. Our result is in disagreement with the calculation quoted there.

5. Summary

Various models contain a doubly charged Higgs boson. A particularly interesting class of models have a $Y = 1$ triplet Higgs, which can give a Majorana mass to neutrinos. The left-right symmetric model is an example of such a model. Although the triplet vev is constrained by the ρ parameter, its magnitude may be still substantial. In this case, the doubly charged Higgs decays dominantly to four-fermion final states via intermediate WW. Existing searches for H^{++} in Z decays only looked for either dilepton modes or quasistable massive tracks. A new analysis is thus called for to exclude the entire mass region $m_H < m_Z/2$.

We have also derived the four-fermion decay rate for a neutral Higgs boson. This decay mode may be important for a special class of Higgs which has a reduced Yukawa coupling to quarks and leptons.

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Figure Captions

Fig. 1. Feynman diagram for the process $H^{++} \to f_1 \bar{f}_2 f_3 \bar{f}_4$.

Fig. 2. Feynman diagrams for the process $H^{++} \to f_1 \bar{f}_2 f_1 \bar{f}_2$.

Fig. 3. Decay width for $H^{++} \to f \bar{f} f \bar{f}$. Three generations of quarks and leptons except $t\bar{b}$ are included in the final states. The solid line shows the numerical result with (2.7), whereas the dotted line is the pointlike approximation with (2.9).

Fig. 4. Decay signatures of H^{++} for $m_H = 40\,\mathrm{GeV}$. The solid lines correspond to the ratio of four-fermion to dilepton branching fractions $R = 0.1$, 1, and 10. The dash-dotted lines give the contour for the decay length $\ell = 1$ cm and 1 m. The laboratory limit [11], $m(\nu_\tau) < 31\,\mathrm{MeV}$, and cosmological limit [12] for a stable ν, $m(\nu) < 50\,\mathrm{eV}$, are also shown by the dashed lines.

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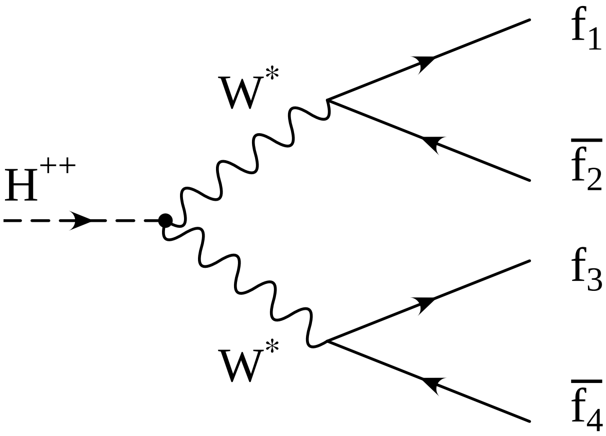


Fig. 1

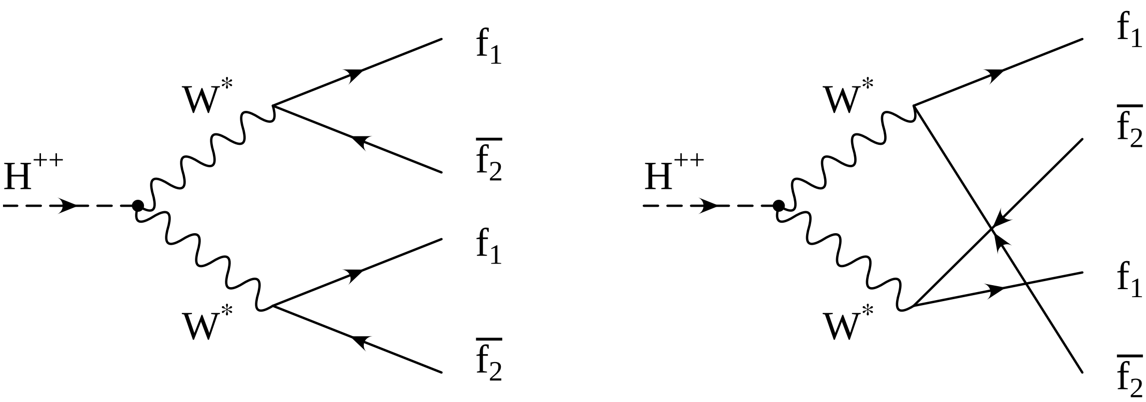
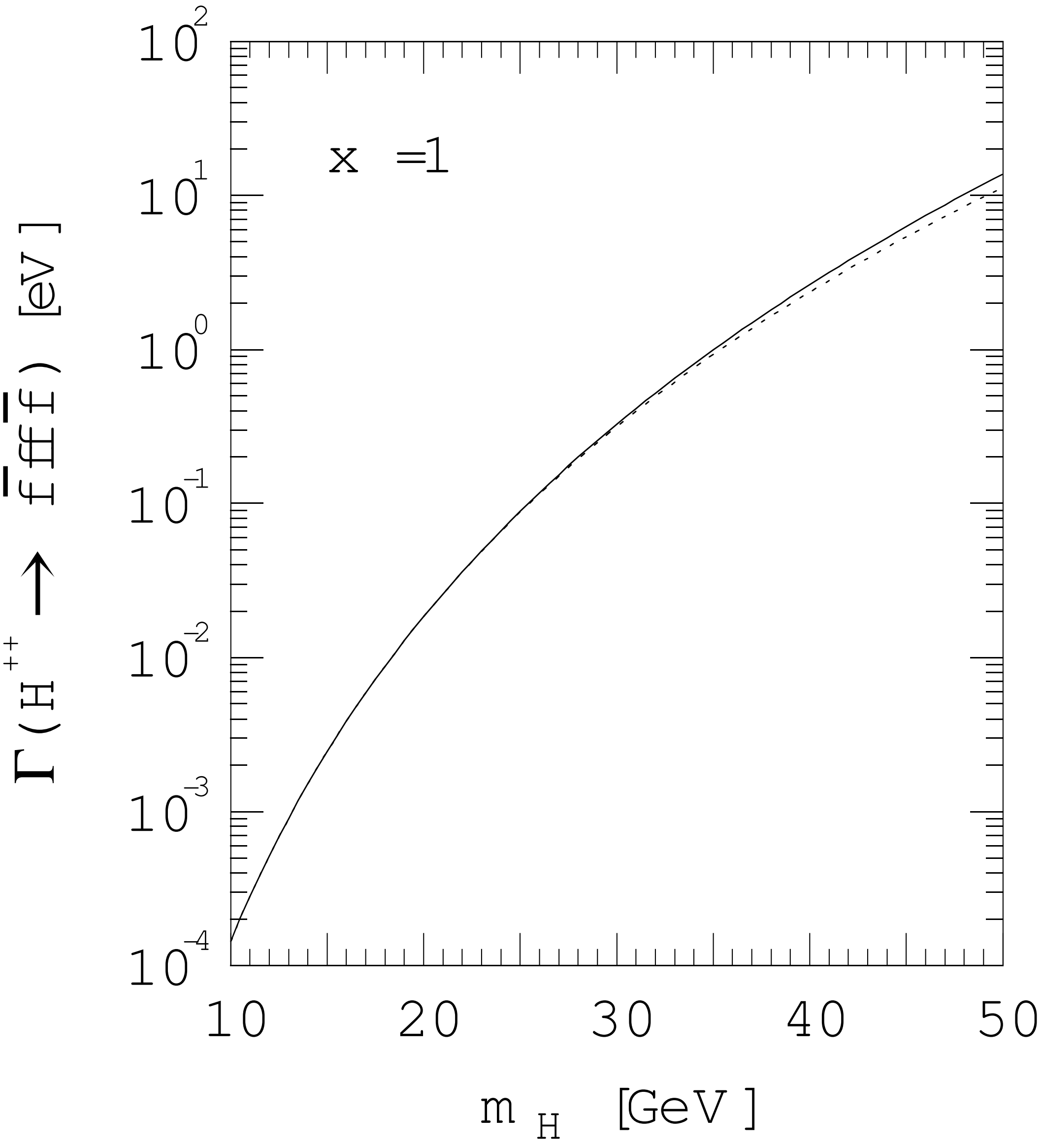
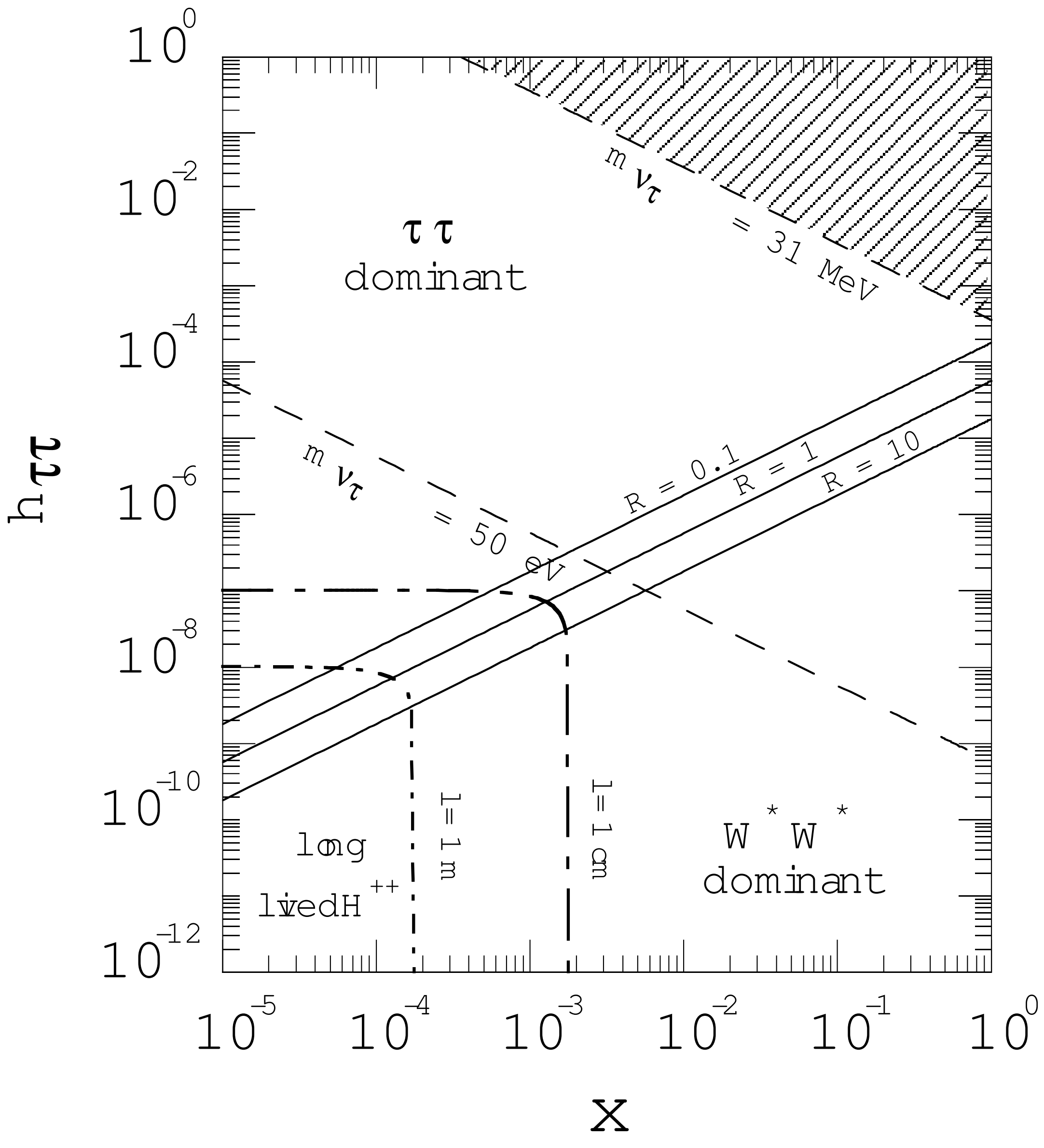


Fig. 2



x =1
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\Gamma(H^{++} \to f\bar{f}f\bar{f})$ [eV]
10
20
30
40
50
m_H [GeV]

Fig. 3



10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$h_{\tau\tau}$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
x
$\tau\tau$
dominant
$m_{\nu_\tau} = 31$ MeV
$m_{\nu_\tau} = 50$ eV
R = 0.1
R = 1
R = 10
l = 1 m
l = 1 cm
long
lived H^{++}
$W^* W^*$
dominant

Fig. 4